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IX.

METHODS OF MEASURING ELECTRIC CURRENTS OF GREAT STRENGTH; TOGETHER WITH A COMPARISON OF THE WILDE, THE GRAMME, AND THE SIEMEN'S MACHINES.

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Presented, Oct. 9th, 1878.

THE measurement of electric currents of great strength can be classed under four heads: No. 1. The Galvanometric Method. No. 2. The Electrometer Method. No. 3. The Heat Method. No. 4. The Electrodynamometer Method.

No. 1. *The Galvanometric Method.*

With a galvanometer of small resistance and of large radius, it is necessary to bring the deflection to the neighborhood of 45° by means of a shunt of very small resistance. The errors increase when the deflections exceed 45° in a divided circuit, and, by the use of a shunt of small resistance, any error in the measurement of this small resistance multiplies the whole observation by this error.

By the use of a cosine galvanometer which I devised in 1871, and published in the "American Journal for Science" for that year, the use of shunts can be modified; but there are difficulties from the dip of the needle and from want of accuracy in graduations of the circle which measures the deflection of the moving coil from the vertical plane.

In practice, it is very inconvenient to find a suitable shunt which will answer for a wide range of experiments, and different shunts have to be used. Moreover, the heating of the shunt multiplies the observations by an error. In short, by the use of a shunt method, we measure a large quantity by observations upon a hundredth or a thousandth part of itself, and proceed from a small quantity to a large one which is a fundamentally defective method.

No. 2. *The Electrometer Method.*

By means of a suitable electrometer, the difference of potential of two points in a closed circuit can be measured; and, from this, the electromotive force in volts can be estimated. The difficulty of dealing

with static electricity in electrical measurements is well known. Leakage, want of constancy of charge in the electrometer, nay, impossibility of maintaining a charge in certain localities, limit the use of this method, even if the results obtained were not approximate.

No. 3. *Heat Method.*

By the use of the law that the heat developed in a circuit is expressed by $H = C^2Rt$, where C is current in Vebers, $R =$ resistance, $t =$ time, we can deduce C by measuring the rise of temperature of a given volume of water. Measurements of temperature are especially fraught with difficulties on account of conduction, radiation, and errors of thermometers, beside consuming time in waiting for the proper conditions for a given experiment.

No. 4. *The Electrodynamometer Method.*

The principle of Webers' electrodynamometer is well known. The electric current passes down one wire of the bifilar suspension of a movable coil and up the other, and then through fixed coils surrounding the movable coil. Maxwell, in his "Electricity and Magnetism," Vol. II. p. 332, remarks: "Webers' form of the electrodynamometer, in which one coil is suspended within another, and is acted on by a couple tending to turn it about a vertical axis, is probably the best fitted for absolute measurements." With powerful currents, however, it is necessary to shunt this instrument, and the errors inherent in this method are introduced. Even with moderate currents, the directive force of the bifilar suspension is changed by the elongation of the wire from a rise in temperature. If we keep within the point at which the wires are elongated, the deflections are slight and subject to error of observation.

In working with dynamo-electric machines, it is important that we should avoid the method of shunts; for the entire resistance of the circuit is generally of the same order of magnitude as the shunts employed. It is necessary that we measure the whole strength of the current directly at the same time that we measure the work consumed in driving the dynamo-electric machine, the velocity of the machine, and the resistance of the circuit. It is also important to eliminate local attractions. The time consumed in measuring the current strength should be small.

The instrument described in this paper fulfilled the conditions prescribed.

Fig. 1 shows the general aspect of the apparatus. The large fixed coils were made of copper bands, 35 mm. broad and 1 mm. thick.

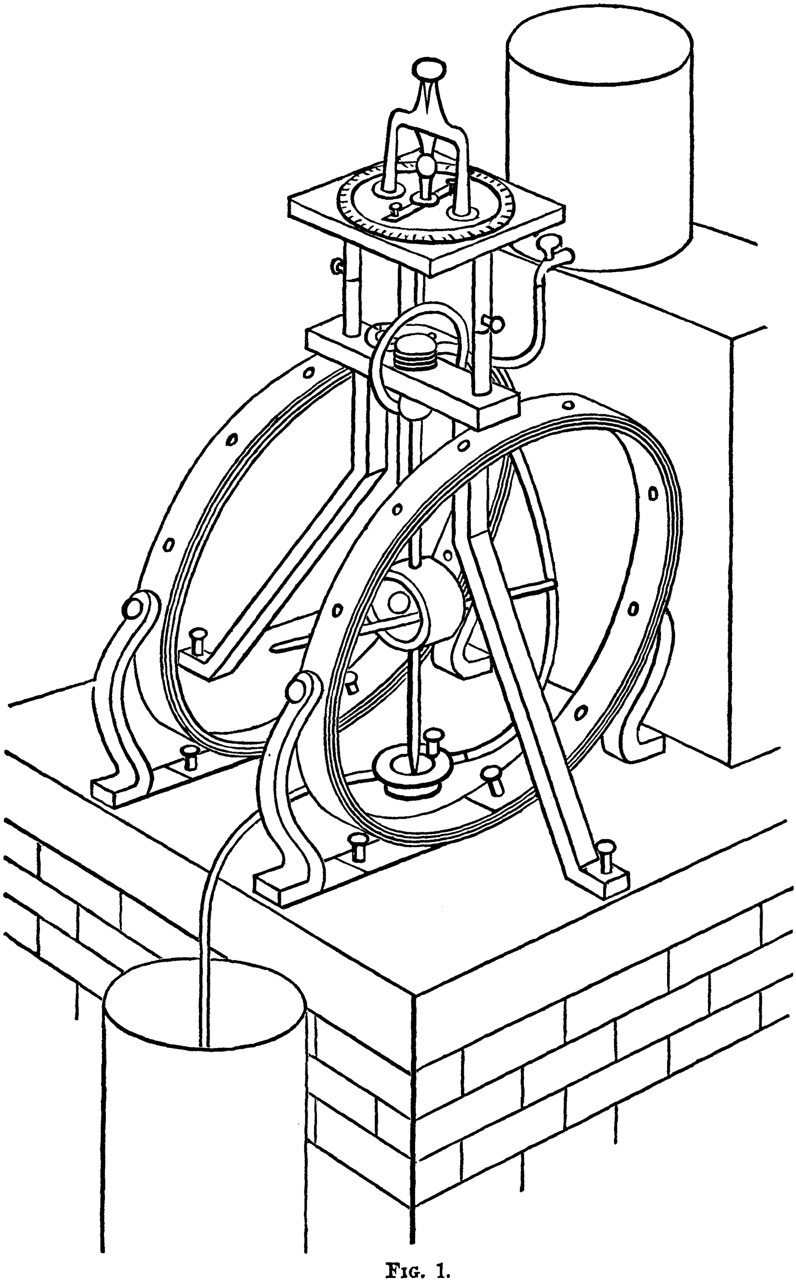

Fig. 1.

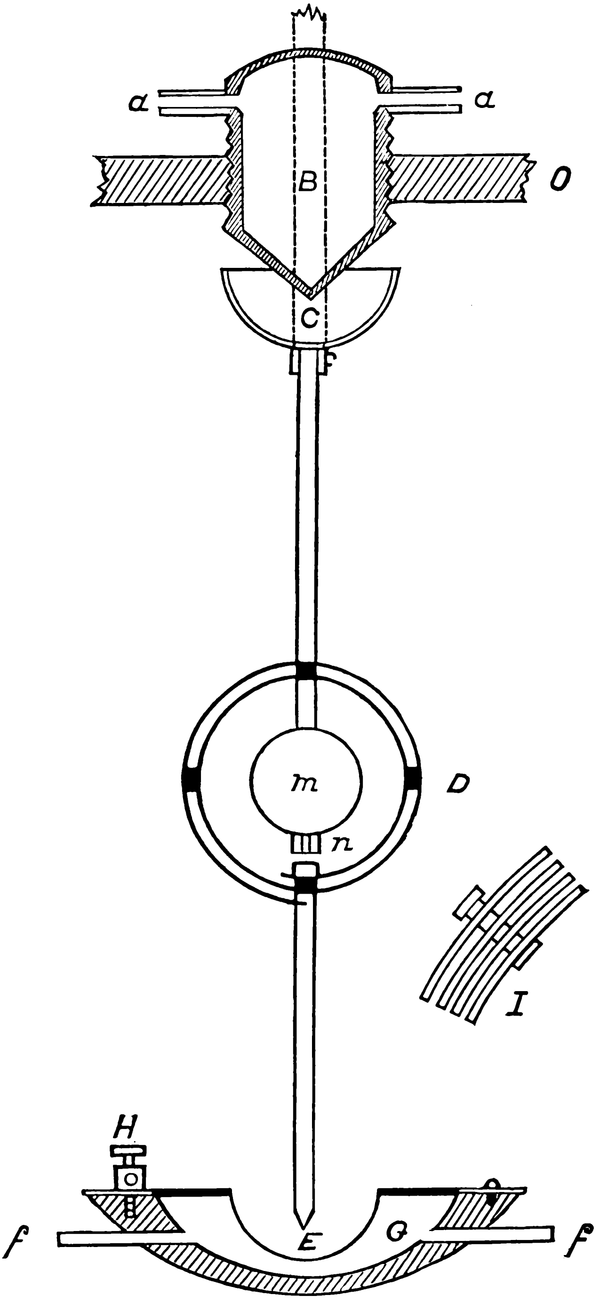

FIG. 2.

There were twelve coils, six on each side of the movable coil which is shown with its suspension between them. The large coils were insulated from each other by vulcanite washers, and held together by brass rivets which were insulated by vulcanite cylinders. The coils were placed at a distance apart equal to their thickness, and thus allowed currents of air to pass freely between them. This arrangement is shown at I, Fig. 2. The bifilar suspension is connected with a graduated circle which read by means of verniers to one minute. The tangent and clamping screws of the torsion head are not shown in the figure. The general arrangement was similar to that used by Mr. Latimer Clark, and figured in Maxwell's "Electricity," with the exception that the graduation was not upon a cylinder, but was on a plane, and the graduated circle was such as is used on spectrometers. The torsion head admitted of vertical adjustment by means of the hollow cylinders at its points of support, in addition to the vertical adjustment of the pulley by means of which the tension upon the suspending threads was equalized. In the ordinary form of electrodynamometer, the current passes down one suspending wire and up the other. In my dynamometer, this is not the case, as is shown in Fig. 2. Therefore, the suspension can be made of strands of silk or any suitable material, according to the sensitiveness desired. In the actual use of the instrument with powerful current, it was found necessary to use steel wire in order to increase the directive force, so great were the deflections.

The movable parts are best shown in Fig. 2. The construction of the central coil is shown at D. The water enters at a, passes out at a after cooling the hollow chamber B, which admits of adjustment, and then flows by rubber tubing to f; and, after cooling the mercury cup E, flows out through f. G is the water-chamber which answers to B. At n, below the mirror m, is a bar upon which are hung cylindrical weights to determine the moment of inertion to alter the sensitiveness. Only one coil and a half are shown in the figure. The electric current enters at H, passes through the mercury cup to E, then to C, and thence by the hollow cup to O, and then around the outer coils.

A telescope with scale was employed to read the deflections; but it was found better, in practice, to use the graduated circle of the torsion head and bring the movable coil back to zero. In this case, we have from the theory of the electrodynamometer: —

$$C^2 = \sqrt{\frac{F}{Gg}} \sin \theta ;$$

and the effect of the earth and local attraction are eliminated. By this method of observation, no telescope and scale are needed. It is only necessary to bring the point of the bar which passes through the movable coil to a fixed point. The mercury in the pivot cups serves to dampen the vibrations of the movable part of the apparatus; and it was found that readings could be taken quicker than by galvanometric methods.

Theory of Instrument.

("*Maxwell's Electricity,*" *Vol. II. page* 329.)

$$C^2 = \frac{F \tan \theta.}{Gy \cos \beta.}$$

Where

$C =$ current.

$F =$ directive force.

G and $g =$ constants of fixed and movable coils.

$\beta =$ angle of coil with magnetic meridian.

If the torsion head of the instrument can be adjusted so that the deflection is zero, and $\theta = - \beta$

$$\text{we have } C^2 = \frac{F}{Gg} \sin \beta.$$

The value of F was determined by several methods. Since

$$Ft^2 = \pi^2 A,$$

where t is time of vibration,
and $A =$ moment of inertia,

it is necessary to determine both the time of swing and the inertia. The times of swinging were obtained by means of a chronograph upon which seconds were recorded by the side of the records produced by breaking an electric circuit at the instant the movable coil passed the middle of its vibrations. The moment of inertia was first determined experimentally by adding known cylindrical weights, and determining the new time of vibration.

We thus have

$$A = k \left(\frac{t^2}{(1 + \frac{w}{w_1})\, t_1^2 - t^2} \right)$$

$$\text{and } k = w \left(l^2 + \frac{r^2}{2} \right)$$

where $k =$ moment of inertia of added cylindrical weights; $w =$ weight of cylinders in milligrammes; $l =$ distance of point of suspen-

sion of cylinders from axis; $r =$ radius of cylinders; and w, mass of moving parts before w was added. The dimensions being in millimetres.

From these expressions, we obtain

$$F = \frac{\pi^2 k}{(1 + \frac{w}{w_1})\, t_1^2 - t^2}$$

The constants G and g were calculated from the actual measurements of the coils, which could be made with great accuracy, since all the parts were large.

The constants were as follows: —

$$\text{mean radius } r = 153.3 \text{ mm.}$$
$$Gg = 1631.45$$
$$\frac{F}{Gg} = 656.626.$$

The constant was also determined by the running the same current through the electrodynamometer and a tangent galvanometer of one turn of copper wire, whose radius was r and whose constant was equal to $\frac{rT}{2n\pi}$.

In this case $C^2 = \frac{r^2 T^2}{4n^2\pi^2} \tan^2\theta = \frac{F}{Gg} \sin\varphi$, and $\frac{F}{Gg} = \frac{r^2T^2}{4n^2\pi^2} \cdot \frac{\tan^2\theta}{\sin\phi}$,

where $T =$ horizontal form of earth's magnetism.
$r =$ radius of galvanometer coil.
$\theta =$ deflection of galvanometer.
$\varphi =$ deflection of electrodynamometer.

The result obtained in this way closely agreed with that obtained by the previous method.

No difficulty was experienced from the heating produced by currents of even eighty vebers, when the current was allowed to run for a long period through the instrument; as long as the stream of water was maintained around the mercury cups, even a small immersion of the points of the axis of the movable part of the instrument did not result in heating. By this instrument, therefore, the whole current could be measured without shunting. At first, the metal pivots which dipped into the mercury were tipped with aluminum; but, when a strong current passed through them, the mercury was disturbed by an apparent ebullition, and the mercury speedily was covered with a black deposit. It was found that copper points would answer perfectly well. Dis-

tilled mercury was used in all cases: it answered the double purpose of conducting the current and bringing the vibrations quickly to rest.

Through the courtesy of Captain Breese, U. S. N., in charge of the U. S. Torpedo Station at Newport, R. I., who obtained permission for me to use the dynamo-electric engines at that place, I was enabled to make a series of measurements with the dynamometer described above.

The resistances used consisted of large bands of german silver, each in the neighborhood of $\frac{1}{10}$ of an ohm resistance. The foot-pounds of work consumed were measured by a Batchelder's dynamometer,* which is fully described in Dingler's "Polytechnic Journal," 1844, Vol. II. This dynamometer is not suitable for the measurement of small or great horse-power; but it answered very well in the limits of velocities and horse-powers to which I confined myself. An accurate measure of the work consumed in running a dynamo-electric machine upon a closed circuit would require the use of gearing instead of belting; for it is difficult to estimate the slip of the belting. On account of the error introduced from this latter-mentioned clause, I have given the whole work required to run each machine on a closed circuit. The slip on an open circuit would be small, but on a closed circuit might be very large. The machines were run under the same conditions of shafting and pulleys. It was estimated that the Siemens required 0.031 horse-power on an open circuit, and the Gramme 0.206 to 0.328 horse-power. The term efficiency denotes the ratio of the equivalent in metre grammes of the current produced to the metre grammes consumed in running the dynamo-electric machine. Since one veber through one ohm

$$= C = \frac{10^5}{10^7} = 10^{-2}$$

the work $w = C^2Rt = (10^{-2})^2 \times 10^7 = 10^3 = 1000$ units of work, and dividing by the unit employed we have

equivalent of 1 Veber = 102 metre grammes,
one foot-pound = 138 metre grammes.

* For which I am indebted to the Massachusetts Institute of Technology.

WILDE MACHINE (*large size*).

Resistance of circuit in ohms.	Current in Vebers per sec.	Speed of machine per min.	Metre grammes consumed per sec.	Equivalent of current in metre grammes per sec.
.594	62.33	548	350.658	235.480
.733	61.76	508	392.403	285.293
.857	43.82	532	283.107	167.907
.907	60.25	500	453.123	335.966
1.039	39.28	520	298.356	163.682
1.120	43.44	548	343.827	215.660
1.241	50.43	504	542.685	322.047
1.453	44.94	520	553.311	309.658
1.593	47.51	536	638.765	366.910
2.305	32.86	528	643.632	253.968

The measurements with the Wilde machine were made with an electrodynamometer similar to that described in Maxwell's "Electricity and Magnetism." It was constructed on the Helmholtz Gaugain principle, and had a resistance of 58.9 ohms. A shunt of .1 ohm had to be employed, and the instrument was also coupled in multiple arc to avoid the lengthening of the bifilar suspension.

GRAMME MACHINE (*large size*).

Resistance of circuit in ohms.	Current in Vebers per sec.	No. of revolutions of armature per min.	Metre grammes consumed per sec.	Equivalent of current in metre grammes per sec.
.675	86.0	432	589.743	509.418
.760	75.6	462	534.336	442.211
.781	75.6	452	607.200	455.377

SIEMENS MACHINE (*large size*).

Resistance of circuit in ohms.	Current in Vebers per sec.	No. of revolutions of armature per min.	Metre grammes consumed per sec.	Equivalent of current in metre grammes per sec.
.973	79.8	264.	831.105	632.255
1.055	68.8	294.5	743.820	509.569
1.066	66.0	325.	839.454	472.805

I add a few data in regard to the dimensions of these machines, which are partly taken from the reports of the Secretary of the Navy for 1877, and partly from the Station records which were generously placed at my disposal.

The Gramme Machine.—This machine weighs about 2,700 pounds, stands 30″ high, is 40″ long and 34″ wide. It is driven by a pulley 15″ in diameter. The armature moves with very little friction. The field of force coils are flat, and there are four of these, each about 10″ long, $3\frac{3}{4}$″ deep, and 22″ wide. The armature resistance is 0.129 ohms, the field resistance 0.212 ohms; thus making .341 ohms for the total internal resistance. The total weight of wire in the machine is 483 pounds; or the weight of wire is nearly 18 per cent of the total weight of the machine.

Siemens Machine, or Heffner von Altenek Machine, built by the Siemens Bros. This machine is 61″ in length, 28″ in breadth, and 12″ in height. The armature is nearly 34″ long, and $9\frac{1}{2}$″ external diameter. It is formed by winding 98 pounds of two insulated wires longitudinally, and in eight divisions, around a thin and hollow brass cylinder. Within this hollow cylinder is a hollow stationary cylinder of cast iron, supported by bearings that pass through the brass cylinder. The commutator has eight divisions, which are eight sector-shaped sheets of brass insulated from, but attached to, the face of a plate which is outside of one of the bearings of the brass cylinder. Two collectors or brushes trail upon and press against these sectors: these brushes have a bearing so extensive as to short circuit or bridge over the edge of two sectors. The spark of the commutator is quite insignificant. This machine differs from all others in this respect: the armature simply moves a wire through a field of force, and not a soft iron core covered with wire. The resistance of the entire circuit, field of force, connected for conductivity, is .586 ohms. The normal velocity of machine is from 370 to 380 revolutions per minute.

Wilde Machine.—"This resembles, in some respect, the Hjorth machine of 1855, with the permanent magnet omitted. It has two armature circuits: one with current uniform in direction for the purpose of maintaining the magnetism of the field; and the other for producing the electric light. The current from this last circuit is a to and fro current, without commutator.

"The armature wire weighs 28 pounds, and is divided into two circuits; about 7 pounds of it having a resistance of .454 ohms furnishes the current which maintains the field. The remainder, 21 pounds, having a resistance of .074 ohms, maintains the to and fro current. About 325 pounds of wire are distributed in 24 coils to make up the electro-magnetic field which has a resistance of 2.83 ohms. These coils are $10\frac{1}{4}$″ in length and $3\frac{7}{8}$″ in external diameter, having soft round cores 2″ in diameter. There are 24 armature cores and coils, one half

on each side of a central cast-iron wheel $1\frac{1}{2}''$ thick. The central diameter of this wheel is $18''$ nearly. The whole weight of wire in this machine is nearly 354 pounds." The normal velocity of machine is about 600 revolutions. A greater rate of speed would have increased, to a certain extent, the currents produced by the Siemens and the Gramme machines: on the other hand, more horse-power would have been necessary to attain this increased speed. The Wilde machine requires more horse-power to run it, as the resistance of the outside circuit increases. This is due to the construction of the machine, and is not the case with the Siemens and the Gramme machine. A certain proportion between the resistance of the machine and that of the outside circuit is undoubtedly best for greatest efficiency of dynamo-electric machines; and a certain velocity is necessary to attain the greatest efficiency.

From my experiments, I should class the machines as follows: —

Gramme,
Siemens,
Wilde.

Theoretically, the Siemens machine should give the best results. At the time of my experiments, the Siemens machine suffered the disadvantage of being run at a less rate of speed than the other machines.

I hope to pursue these tests under conditions resulting from higher speed. Generally speaking, that machine is the best which gives the greatest efficiency at low rates of speed; for the necessity of high speed introduces much that is detrimental to the locality of the machine and to the machine itself. At the present time, alternating machines are coming into notice again, in connection with electric lighting; and a suitable electrodynamometer is desirable in the measurement of the current produced by these machines. The instrument which I have tested above seems to fulfil the proper conditions.

My thanks are due to the officers of the station for their generous assistance and free disposal of the resources of their electrical department.